Cosmic ray anomalies and DAMA experiment in an Extended Seesaw Model

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We show that an extended seesaw model proposed to achieve low scale leptogenesis can resolve the excess positron and electron fluxes observed from PAMELA, ATIC and/or Fermi-LAT, and simultaneously accommodate the recent DAMA experimental results. In this approach, an extra vector-like singlet neutrino S and a singlet scalar field ψ, which are doubly coexisting dark matter candidates, are responsible for the origin of the excess positron and electron fluxes and the observation of the DAMA annually modulated signal. It is also shown that the DAMA results and the other null results from direct searches for dark matter can be reconciled if 3 GeV $\lesssim m_\psi \lesssim$ 8 GeV. On the other hand, in addition to $SU(2)_L$ doublet Higgs field H, the light singlet scalar field Φ, which is demanded to successfully construct the coexisting two-particle dark matter scenario and whose mass is taken to be just below 1 GeV, may play an essential role in resolving the PAMELA, ATIC and/or Fermi-LAT anomalies.

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[1]*Introduction.* The quest for identification of the missing mass of our universe is one of the most fundamental issue in astroparticle physics and cosmology. The evidence for non-baryonic dark matter (DM) inferred from a combination of cosmological and astrophysical phenomena becomes more and more convincing, which alludes the existence of new physics beyond the standard model (SM). Recently, the DAMA collaboration reported strong evidence for model independent annual modulation signature in the rate of single scattering events by combining data from DAMA/NaI and DAMA/Libra with 8.2σ significance [1]. This modulation signal can be interpreted by the scattering of weakly interacting massive particles (WIMPs) forming the DM halo of our galaxy. While the interpretation of the DAMA results in terms of the DM-nucleon elastic scattering is almost in conflict with the null results of various other direct detection experiments [2, 3], there is a small region of WIMP parameter space which can simultaneously accommodate DAMA experiment and the null results of the other direct DM detection experiments [4, 5]. On the other hand, recent experiments measuring high energy cosmic rays may offer important insights into the existence of DM. The PAMELA experiment has presented a significant positron excess flux over the expected background with no excess in the corresponding anti-proton flux [6]. This result confirmed previous observation of a positron excess by HEAT and AMS [7]. The ATIC/PPB-BETS experiment has shown significant excess electron and positron flux at energies around 300-800 GeV [8, 9]. More recently, Fermi-LAT experiment have also shown an excess electron and positron flux in the same energy range as in ATIC but its strength was not strong compared to ATIC [10]. Since the positron excess observed in the PAMELA experiment is not accompanied by an anti-proton excess, an unified understanding of those experimental results based on DM demands new interactions through which the DM primarily self annihilates [11, 12] (or decay [12, 13]) into only leptons, and a 'boost' factor which could either have an astrophysical origin or have a particle physics origin such as Sommerfeld enhancement because the required annihilation cross section in the galactic halo is orders of magnitude larger than the thermal relic expectation [14, 15, 16]. So, it is likely that the DAMA annually modulated signal is not reconciled with the cosmic ray positron and electron excess in the framework of one and only one DM scenarios.

Recently, we have proposed an extended seesaw model to simultaneously and naturally accommodate tiny neutrino masses, low scale leptogenesis and dark matter candidate by introducing extra singlet neutrinos and singlet scalar particles on top of the canonical seesaw model [17, 18]. Furthermore, we have proposed a doubly coexisting two-particle DM scenario [19] by allowing both an extra singlet Majorana neutrino S and a light singlet scalar particle ψ two DM candidates. Such a scenario containing more than one DM may be desirable in the case that there exist a few incompatible phenomena which are very hard to reconcile in the scenarios with only one DM.

The purpose of this letter is to investigate how both DAMA experimental results and the cosmic ray positron and electron excess observed from PAMELA, ATIC and/or Fermi-LAT experiments are simultaneously explained in the extended seesaw model with doubly coexisting two-particle DM proposed in [19]. In this work, we slightly modify the model proposed in [19] by replacing extra singlet Majorana neutrino with singlet vector-like neutrinos so as to simply resolve the cosmic ray anomaly while keeping to accommodate tiny neutrino masses and

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low scale leptogenesis. We notice that to achieve our doubly coexisting two-particle DM scenario in the renormalizable framework as shown in [19], an extra singlet Higgs scalar field Φ is necessarily introduced, which may open up new channels of DM annihilations. As will be shown later, in this scenario, this scalar field Φ may play an essential role in resolving the unexpected electron and positron fluxes measured at PAMELA, ATIC and/or Fermi-LAT if the mass of Φ has rather small around just below 1 GeV so as for the annihilation cross section to be enhanced via a mechanism first described by Sommerfeld [14, 15, 16]. Once this new force carrier Φ is included, the possibility of a new dominant annihilation channel $SS \to \Phi\Phi$ opens up. The Φ mixes with the Higgs allowing it to decay into the final state fermions, and if the Φ is taken to be light, it is kinematically constrained to decay to mostly lepton pairs preventing from producing antiprotons, so that the excess of positron and/or electron observed can be accounted for. In addition, the DAMA results will be explained by considering the singlet scalar ψ as the lightest DM candidate with mass of order a few GeV. Thus, the DAMA results, the excess positron and electron fluxes produced from the cosmic rays, low scale leptogenesis and light neutrino masses can be simultaneously accommodated in our model proposed.

The doubly coexisting two-particle DM scenario is achieved by the following Lagrangian

$$\begin{aligned}\mathcal{L} &= \mathcal{L}_0 + (Y_D \bar{L}HN + Y_S \bar{N}\psi S + h.c.) + M_N N^T N \\ &+ Y_\Phi \bar{S}\Phi S - m_{\underset{S}{0}} \bar{S}S + \frac{1}{2}m^2_{\psi^0}\psi^2 - \frac{\lambda_s}{4}\psi^4 - \lambda H^\dagger H \psi^2 \\ &+ \frac{1}{2}m^2_{\Phi^0}\Phi^2 - \frac{\lambda_2}{4}\Phi^4 - \lambda_3\psi^2\Phi^2 - \lambda_4 H^\dagger H \Phi^2, \qquad (1)\end{aligned}$$

where the first term is the Lagrangian of the SM and kinetic terms of the singlet fields, and L, N, S and ψ stand for $SU(2)_L$ lepton doublet, singlet heavy Majorana neutrino, singlet vector-like neutrino composed of two Weyl fermions, and light singlet scalar, respectively. Note that S and ψ are our doubly coexisting dark matter candidates. Finally H and Φ denote the $SU(2)_L$ doublet and singlet (Higgs) scalar fields, and m_Φ is assumed to be smaller than 1 GeV.

In this model, light neutrino masses can be achieved by the usual canonical seesaw mechanism and low scale leptogenesis of order 1-10 TeV leptogenesis can be realized via the decay of the lightest heavy Majorana neutrino N. Similar to the case in Ref. [17, 18], there exists a new contribution to lepton asymmetry ε_1 arisen from a self energy correction of the vertex generated due to the Yukawa interaction term $Y_S\bar{N}\psi S$. For $M_{N_1} \simeq M_{N_2} \lesssim M_{N_3}$, the lepton asymmetry is approximately given by

$$\begin{aligned}\varepsilon_1 &\simeq -\frac{1}{8\pi}\Big[\frac{M_{N_2}}{v_E^2 W}\frac{Im[(Y_D^* m_\nu Y_D^\dagger)_{11}]}{(Y_D Y_D^\dagger + Y_S Y_S^\dagger)_{11}} \qquad (2) \\ &+ \frac{\sum_{k\neq 1} Im[(Y_D Y_D^\dagger)_{k1}(Y_S Y_S^\dagger)_{1k}]}{(Y_D Y_D^\dagger + Y_S Y_S^\dagger)_{11}}\Big]\Big|\frac{M_{N1}}{M_{N_2} - M_{N_1}}\Big|.\end{aligned}$$

Since the size of $(Y_S)_{2i}$ is not constrained by the out-of-equilibrium condition, large value of $(Y_S)_{2i}$ is allowed for which the second term of Eq. (2) can dominate over the first one and thus the size of ε_1 can be enhanced. Again similar to Ref. [17, 18], the successful leptogenesis can be achieved for M_{N_1} of order a few TeV, provided that $(Y_S)_{2i}/(Y_D^*)_{2i} \sim 10^3$ and $M^2_{N_2}/M^2_{N_1} \sim 10$.

In order to guarantee the stability of the 2DM candidates, we impose the discrete symmetry $Z_2 \times Z_2'$ under which all the SM particles and Φ are $(+,+)$, the singlet neutrino S is $(-,+)$ and the singlet scalar boson ψ is $(+,-)$. Now, we demand that the minimum of the scalar potential is bounded from below so as to guarantee the existence of vacuum and the minimum of the scalar potential must spontaneously break the electroweak gauge group, $< H^0 >, < \Phi > \neq 0$, but must not break $Z_2 \times Z_2'$ symmetry imposed above.

After spontaneous symmetry breaking, the part of the scalar potential is given by

$$\begin{aligned}V &= \frac{1}{2}m_\psi^2\psi^2 - \frac{1}{2}m_h^2 h^2 - \frac{1}{2}m_\phi^2\phi^2 + 2\lambda_4 v_h v_\phi h\phi \\ &+ \frac{\lambda_s}{4}\psi^4 + \frac{\lambda_1}{4}v_h h^3 + \frac{\lambda_1}{16}h^4 + \frac{\lambda_2}{4}\phi^4 \\ &+ \lambda_2 v_\phi \phi^3 + \frac{\lambda}{2}\psi^2 h^2 + \lambda v_h h\psi^2 + \lambda_3\psi^2\phi^2 + 2\lambda_3 v_\phi \phi\psi^2 \\ &+ \frac{\lambda_4}{2}h^2\phi^2 + \lambda_4 v_\phi h^2\phi + \lambda_4 v_h h\phi^2 + h.c., \qquad (3)\end{aligned}$$

where $m_\psi^2 = m^2_{\psi^0} + \lambda v_h^2 + 2\lambda_3 v_\phi^2$, $m_h^2 = \frac{1}{2}m^2_{H^0} - \frac{3}{4}\lambda_1 v_h^2 - \lambda_4 v_\phi^2$, $m_\phi^2 = m^2_{\phi^0} - 3\lambda_2 v_\phi^2 - \lambda_4 v_h^2$. Here, we have adopted $\sqrt{2}H^T = (h, 0)$ and shifted the Higgs boson H and the singlet Higgs scalar Φ by $H \to h + v_h$ and $\Phi \to \phi + v_\phi$, respectively. Since there exists a mixing mass term between h and ϕ, we rotate them with $\phi = sh' + c\phi'$ and $h = ch' - s\phi'$, where s and c are $\sin\theta$ and $\cos\theta$, respectively.

For $m_\phi \lesssim 1$ GeV and $m_{_S} >> m_\phi$, the singlet neutrinos S annihilate into mostly $\phi\phi$ due to the cubic coupling of ϕ in Eq. (3). The ϕ's can then subsequently decay into SM particles, which arises due to their mixing with the Higgs field h. For the case of $m_\phi = 0.25$ GeV, the ϕ mostly decays to muon pairs, which in turn produce electrons and positrons, and thus the resulting spectra for the electrons and positrons are much harder than typical e^+e^- spectra coming from weak-scale WIMP annihilation as shown in [15, 16].

The amount of cold dark matter in the Universe, which has been determined precisely from 5 year WMAP data [20], is given by $\Omega_{CDM}h^2 = 0.1099 \pm 0.0062$. Assuming the coexistence of two dark matter candidates, the relic abundance observed must be composed of the contributions of both S and ψ, $\Omega_{_S}h^2 + \Omega_\psi h^2 = \Omega_{\rm CDM}h^2$. The relic density of each dark matter species is approximately given by $\Omega_i h^2 \approx (0.1pb)/ < \sigma v >_i \qquad (i = s, \psi)$, where $< \sigma v >_i$ is the thermally averaged product of its annihilation cross section with its velocity. For our convenience,

we define the parameter ε_i as a ratio of $\Omega_i h^2$ to $\Omega_{\rm CDM} h^2$,

$$\varepsilon_i = \frac{\Omega_i h^2}{\Omega_{\rm CDM} h^2} \ , \tag{4}$$

where $\varepsilon_S + \varepsilon_\psi = 1$. In fact, the parameter ε_i represents the fraction of the mass density of each dark matter species in our local dark-matter halo as well as in the Universe. Since the values of ε_i are unknown, we consider a few cases by choosing their values in the analysis. Each $\Omega_i h^2$ can be calculate with the help of the *micrOMEGAs* 2.0.7 program [21] by taking input parameters appropriately.

[2]*Implication for DAMA experiment:* In order to interpret DAMA results [1] in terms of DM-nucleon scattering, we choose ψ, the lighter DM particle of 2DM, to be relevant for the experiment. Note that the heavier DM S of order a few TeV is also demanded in order to explain the high energy cosmic ray anomalies later. To investigate the implication for DAMA experimental results, we first have to estimate the DM-nucleon elastic scattering cross section predicted in our scenario. So far most experimental limits of the direct detection have been given in terms of the scattering cross section per nucleon under the assumption that there exists only one DM candidate. In the scenario of 2DM, the cross section for the WIMP-nucleon elastic scattering σ_{el} is composed of σ_S and σ_ψ [22];

$$\frac{\sigma_{el}}{m_0} = \frac{\varepsilon_S}{m_S}\sigma_S + \frac{\varepsilon_\psi}{m_\psi}\sigma_\psi, \tag{5}$$

with m_0 being the WIMP mass, where we set $m_0 = m_\psi$ as the relevant DM mass for the DAMA experiment.

In our model, the non-relativistic S-nucleon elastic scattering cross section is given by

$$\sigma_S(\text{nucleon}) \approx \frac{1}{4\pi}\Big[\frac{\sin 2\theta Y_\phi m_S m_n^2 f}{(m_n+m_S)v_h}\Big]^2\Big[\frac{1}{m_h^4}+\frac{1}{m_\phi^4}\Big], \tag{6}$$

where m_n is a nucleon mass and f is defined by the relation $f m_n \equiv < n|\sum_q m_q \bar{q}q|n >$ whose size is determined by [23], $0.13 \lesssim f \lesssim 0.62$. For our numerical estimate, we take f to be 0.36. The first and second terms in the parenthesis correspond to the elastic scattering mediated by the Higgs field h and scalar field ϕ, respectively. In the case of scalar ψ-nucleon elastic scattering, the non-relativistic elastic scattering cross section for ψ is given by

$$\sigma_\psi(\text{nucleon}) \approx \frac{1}{4\pi}\Big[\frac{m_n^2 f}{(m_n+m_\psi)v_h}\Big]^2\Big[\Big(\frac{\lambda' c}{m_h^2}\Big)^2 + \Big(\frac{\lambda'' s}{m_\phi^2}\Big)^2\Big] \tag{7}$$

where $\lambda' = \lambda v_h c + 2\lambda_3 v_\phi s$ and $\lambda'' = -\lambda v_h s + 2\lambda_3 v_\phi c$.

In Fig. 1-(a), the pink-colored rectangular area presents the predicted region of the parameter space $(\sigma_{el} - m_\psi)$ in our model for several fixed input parameters given in the panel. Here, we restricted the region of m_ψ to be 3 GeV $\lesssim m_\psi \lesssim$ 8 GeV. We see that there exist some parameter regions compatible with DAMA experimental results as well as other null experimental results. Fig. 1-(b) represent the allowed regions of the parameter space $(\tan\theta, \lambda)$ from the fit to the DAMA results combined with the other null direct search experiments for m_ψ =3, 6, 8 GeV and the same input parameters as in Fig. 1-(a). Before discussing about the indirect experiments on DM, it is worthwhile to notice that such a small mass of ψ taken to be consistent with the DAMA results does not affect e^-/e^+ fluxes observed in the galactic halo.

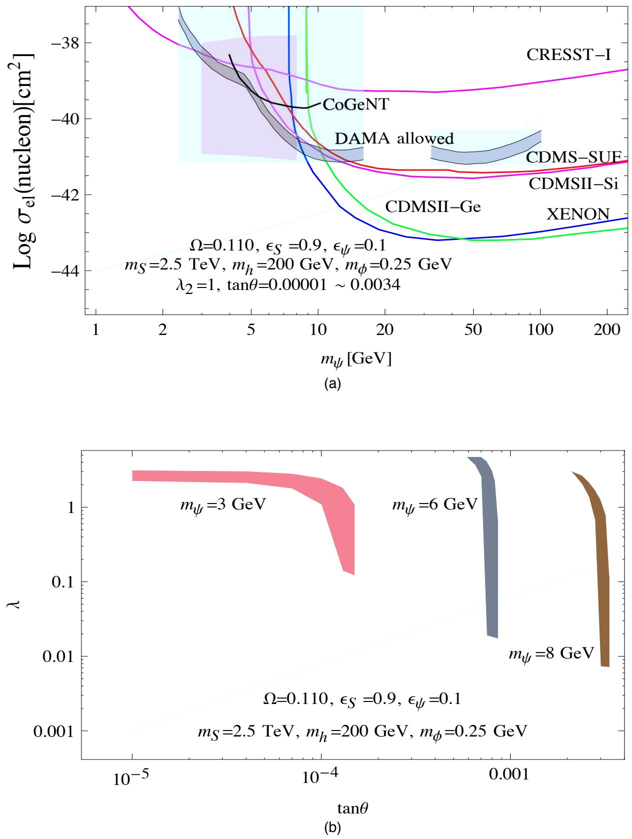

FIG. 1: (a)DM-nucleon elastic scattering cross section *vs.* DM mass. The DAMA experimental results are presented by the grey-colored regions and the pink-colored region corresponds to the prediction of our scenario for given input values presented in the panel and 3 GeV $\lesssim m_\psi \lesssim$ 8 GeV. (b) Allowed regions of the parameter space $(\tan\theta, \lambda)$ from the fit to the DAMA results combined with the other null experiments for m_ψ =3, 6, 8 GeV and the same input parameters as in (a).

[3]*Positron excess from DM annihilations:* Now, let us show that the PAMELA, ATIC and Fermi-LAT data can be accounted for by regarding singlet fermion S as a relevant dark matter much heavier than ψ, which annihilates into dominantly $\phi\phi$, and then the ϕ's subsequently decay into mostly $\mu^+\mu^-$ when m_ϕ is taken to

be 0.25 GeV. In order to calculate the galactic cosmic ray (CR) propagation, we use GALPROP program [24] which simulates the propagation of both cosmic rays and DM annihilation products in the galaxy. The propagation equation for all CR species is given in [24]. To solve the propagation equation under the assumption of free escape of particles at the halo boundaries, we fix the values of the parameters in the propagation equation as follows: the diffusion coefficient $D_0 = 6.10 \times 10^{28}\ cm^2 s^{-1}$, $\delta = 0.33$, the Alfvén speed is 30 km s^{-1}, the convection velocity is 5 km s^{-1}, the gradient of convection velocity is 7 km s^{-1}kpc^{-1} and the normalized electron flux is $1.325 \times 10^{-8}\ cm^{-2} sr^{-1} s^{-1}$MeV^{-1} at 10.6 GeV. We solve the propagation equation by using the code gladef_50p_599278 placed in GALPROP web page [25]. In addition we use an NFW density profile [26], so that the core radius and the local DM density are taken to be 20.0 kpc and 0.3 GeVcm^{-3}, respectively.

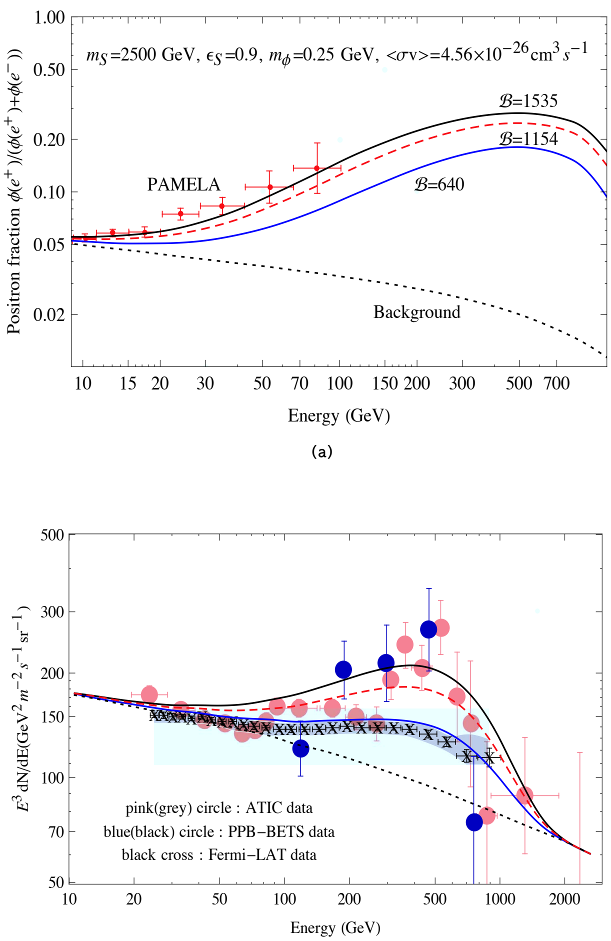

FIG. 2: (a) The ratio of positron to electron plus positron fluxes and (b) total electron plus positron fluxes, arising from the annihilations $SS \to \phi\phi$ and then $\phi \to \mu^+\mu^-$. $\mathcal{B}$ stands for the boost factor relative to $<\sigma v>= 4.56 \times 10^{-26}\ cm^3 s^{-1}$ which is satisfied thermal relic abundance for $\varepsilon_S = 0.9$

In Fig. 2, we present the predictions of our scenario for (a) the ratio of positron to electron plus positron fluxes and (b) the total electron plus positron fluxes, which are originated from $SS \to \phi\phi$, and subsequent decays of the ϕ's into $\mu^+\mu^-$ for the same input values of the parameters. As for input values, we take $\varepsilon_S = 0.9$, $m_S = 2.5$ TeV, $m_\phi = 0.25$ GeV, and $<\sigma v>= 4.56 \times 10^{-26} cm^3 s^{-1}$ which satisfies the thermal relic density of S for the given ε_S. Then, the contribution of S to the local DM density (ρ^0_S) is 0.27 GeV cm^{-3} while that of ψ to the local DM density (ρ^0_ψ) is 0.03 GeV cm^{-3}. In these estimates, we invoke the boost factor ($\mathcal{B}$) reflecting Sommerfeld enhancement through which the halo annihilation rate is enhanced, and it is given by

$$\mathcal{B} \sim \frac{\alpha m_S}{m_\phi}, \tag{8}$$

where α lies between 10^{-3} and 10^{-1} [16]. The each curve in Fig. 2 corresponds to different boost factor, $\mathcal{B}$=1535 (1154, 640) for black solid (red dashed, blue solid) curve. The red dots with error bar correspond to the measurements from the PAMELA (Fig. 2-(a)). The pink (grey), blue (black) circles and black crosses in Fig. 2-(b) correspond to the measurements from ATIC, PPB-BETS and Fermi-LAT, respectively. As one can see from Fig. 2-(a), the PAMELA data for the positron fraction is consistent with the black solid curve corresponding to $\mathcal{B}$=1535. For the same value $\mathcal{B}$ (=1535) as in Fig. 2-(a), the prediction of $E^3 dN/dE$ as a function of E appears to be consistent with the ATIC data as well as the PPB-BETS data, whereas it is inconsistent with the Fermi-LAT data. On the other hand, we see that the prediction with $\mathcal{B}$=640 (blue curve) is consistent with both ATIC data (except for the peak) and Fermi-LAT data, whereas it is inconsistent with the PAMELA data. Therefore, it looks rather difficult to accommodate the PAMELA, ATIC and Fermi-LAT data simultaneously, which may imply that there exist other astronomical sources [27, 28, 29, 30].

[4]*In conclusion,* we have shown that the extended seesaw model proposed to achieve low scale leptogenesis can resolve the anomalies in the indirect detections of annihilation products observed from PAMELA, ATIC and/or Fermi-LAT and simultaneously accommodate the recent DAMA experimental results. In this model, an extra vector-like singlet neutrino S and a singlet light scalar field ψ which are coexisting dark matter candidates, are responsible for the origin of the excess positron and electron fluxes and the observation of the annual modulation signature at DAMA. Furthermore, it has been shown that the DAMA results and the other null results from direct searches for dark matter can be reconciled if 3 GeV $\lesssim m_\psi \lesssim$ 8 GeV. On the other hand, the light singlet Higgs scalar field ϕ, which is demanded to successfully construct the coexisting 2-DM scenario and whose mass is taken to be less than 1 GeV, may play an essential role in resolving the PAMELA, ATIC

and/or Fermi-LAT anomalies.

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